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● *Original Contribution*

APPLICATION OF ACOUSTIC BESSEL BEAMS FOR HANDLING OF HOLLOW POROUS SPHERES

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Abstract—Acoustic manipulation of porous spherical shells, widely used as drug delivery carriers and magnetic resonance imaging contrast agents, is investigated analytically. The technique used for this purpose is based on the application of high-order Bessel beams as a single-beam acoustic manipulation device, by which particles lying on the axis of the beam can be pulled toward the beam source. The exerted acoustic radiation force is calculated using the standard partial-wave series method, and the wave propagation within the porous media is modeled using Biot's theory of poro-elasticity. Numerical simulations are performed for porous aluminum and silica shells of different thickness and porosity. Results indicate that manipulation of low-porosity shells is possible using Bessel beams with large conical angles, over a number of broadband frequency ranges, whereas manipulation of highly porous shells can occur over both narrowband and broadband frequency domains. (E-mail: m.azarpeyvand@bristol.ac.uk) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Acoustic manipulation, Bessel beam, Biot's theory, Porous shell, Microporous.**

INTRODUCTION

Although a great deal of research has been directed toward acoustic handling of rigid, elastic and porous solid particles and shells by means of sonic beams (Azarpeyvand 2012; Azarpeyvand and Azarpeyvand 2013; Marston 2006, 2007, 2009; Mitri 2008, 2009a, 2009b; Zhang and Marston 2011), almost no pertinent studies can be found for porous shells. Acquiring knowledge of the interaction of acoustic fields with spherical and cylindrical porous shells is of great importance, because of the continuing development of new applications in various engineering and medical fields. For instance, periodically arranged cylindrical porous shells can be used as sonic crystal structures to suppress sound propagation for some frequency bands (Sanchez-Dehesa et al. 2011; Umnova et al. 2005). On the micro and nano scale, porous shells have found numerous applications in modern medicine, pharmacology, biotechnology and chemistry. For example, porous shells are now widely used as drug delivery carriers (Andersson et al. 2004; Cheng et al. 2009; Lai et al. 2003; Mal et al. 2003; Radu et al. 2004; Slowing et al. 2008; Zhao et al. 2008) and magnetic resonance imaging (MRI) contrast agents (Campbell et al. 2011; Davis 2002; Gao et al. 2008). In the context of drug delivery carriers, the inner cavity of such particles can store a large amount of drug, and the encapsulating porous shell provides a delivery pathway for drug molecule diffusion. The porous-shelled drug carriers have also been found to be mechanically more stable than some other drug carriers, such as those made of polymers, which have exhibited natural burst release behavior (Jing et al. 2011). Another promising application for porous shells is in MRI contrast agents, used as a coating for high-spin toxic or hazardous metals. Numerous core/porous shell combinations have been tested, and for some, such as zeolite- or clay-enclosed gadolinium complexes and magnetite/silica core-shell (Mag@SiO_2) or FePt@Fe_2O_3 yolk-shell nanoparticles, the results are encouraging (Balkus and Shi 1996a, 1996b; Balkus et al. 1991, 1992).

Contact-free handling, trapping and precise transport of small suspended objects are essential in many fields of science and technology, such as bioengineering, chemical engineering and pharmaceutical sciences. In biologic applications, in particular, the ability to trap and manipulate micro- and nano-particles is of great importance. For example, the performance of drug delivery systems can be

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significantly improved by use of a trapping/transporting system (Suwanpayak et al. 2011). For manipulation of a suspended particle, a force must be applied on its body. This force can be produced optically, electro-kinetically, hydro-dynamically or acoustically. In the latter case, manipulation can be achieved in two different ways, using either a standing-wave field or one single focused beam (Haake and Dual 2004; Liu and Hu 2009; van West et al. 2007; Wu 1991; Yamakoushi and Noguchi 1998; Yasuda et al. 1995). In the standing-wave method, particles are subject to the mechanical force of a standing acoustic wave, generated by one (and one reflector) or more (van West et al. 2007; Vandaele et al. 2005) ultrasonic transducers. In this article, however, we focus our attention on the second technique. In the single-beam technique, as the name implies, only one highly focused ultrasonic transducer is required, and particle handling is made possible by production of a negative axial force, toward the source. Chen and Apfel (1997) and Marston (2006, 2007, 2009) reported that for some material properties and beam types, the acoustic radiation force for a spherical or cylindrical particle can change from repulsion to attraction. This, however, occurs only at certain frequencies and beam operating conditions. Although much research has been conducted on the viability of using single acoustic beam devices, particularly Bessel beams, for handling particles with different mechanical properties in various media, the research in this area has remained limited to very simple cases and has not yet led to an adequate understanding of the mechanism of particle manipulation when more complex particles are of concern (Azarpeyvand 2012; Marston 2006, 2007, 2009; Mitri 2008, 2009a, 2009b).

As stated above, despite the growing attention now being given to different aspects of the application of porous shells, their dynamical behavior when illuminated by an acoustic beam has been the subject of very little research. In this study, we extend the previous investigations by Marston (2006, 2007, 2009), Mitri (2008, 2009a, 2009b) and Azarpeyvand (2012) to the more realistic case of porous shells. The remainder of the paper is organized as follows: The next section is dedicated to the mathematical modeling of the problem. The formulation of a helicoidal Bessel beam is presented, and the radiation force formulations are derived. Biot's theory of motion in poro-elastic media is presented, and the relevant parameters are defined. The numerical results for hollow aluminum and silica spheres of different shell thickness and porosity are presented and discussed.

MATHEMATICAL FORMULATION

Let us consider a porous spherical shell with outer radius a and inner radius b ($h = b/a$). The particle is positioned on the beam axis, and is submerged into and filled with linearly compressible, irrotational and nonviscous ideal fluids. The density and speed of sound in the outer medium are denoted by ρ and c, and those in the core medium by ρ^* and c^*, respectively. The shell is illuminated by a helicoidal Bessel beam, radiating at frequency f ($=\omega/2\pi$), with a conical (or half-cone) angle of β. Figure 1 is a schematic of the problem. In what follows, the Roman numerals I, II, and III designate, the surrounding medium, the porous shell medium and the inner inclusion medium, respectively.

The incident Bessel beam, propagating in free space and in the positive z direction, can be expressed in cylindrical coordinates (R, z, φ) as (Hernández-Figueroa et al. 2008)

$$\Phi^{(\mathrm{inc})}(R,z,\varphi) = \Phi_0 J_\vartheta(\zeta R) e^{i\vartheta\varphi + i\gamma z - i\omega t}, \tag{1}$$

where Φ_0 is the incident field amplitude, $\gamma = k\cos\beta$ and $\zeta = k\sin\beta$ are the longitudinal and traverse wavenumber components of the incident field, with $k = \omega/c$, and $J_\vartheta(\cdot)$ is the Bessel function of order ϑ (Abramowitz and Stegun 1972). The plane wave field can be restored by setting $\vartheta = 0$ and $\beta = 0$, whereas the beam vanishes if $\vartheta = 1$ and $\beta = 0$. It is interesting to note that an axially symmetric Bessel beam is essentially the result of the superposition of plane waves whose wave vectors lay on the surface of a cone having the propagation axis as its symmetry axis and an angle equal to β (conical angle) (Hernández-Figueroa et al. 2008). General intrinsic properties of Bessel beams, such as self-healing, diffraction-free or phase singularity and angular momentum for higher-order Bessel beams, have been explained in Azarpeyvand (2012), Azarpeyvand et al. (2012) and Hernández-Figueroa et al. (2008).

To obtain a closed-form solution to the problem using the partial-wave expansion method, it is necessary to re-express the incident field, eqn (1), in the coordinate system of the particle. Using a standard wave transformation technique (Stratton 1941), one can rewrite the incident sound field in the spherical coordinate system (r, θ, φ) as

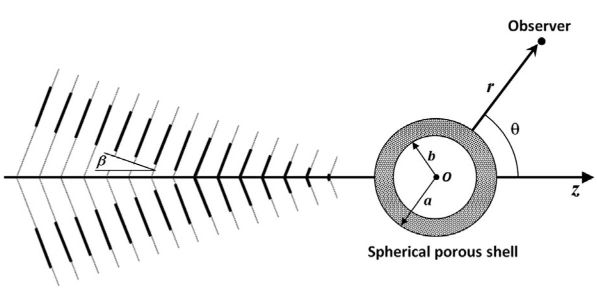

Fig. 1. Acoustic Bessel beam incident on a porous spherical shell.